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International application number: PCT/US05/001295

International filing date: 14 January 2005 (14.01.2005)

Document type: Certified copy of priority document

Document details: Country/Office: US
Number: 60/536,444
Filing date: 14 January 2004 (14.01.2004)

Date of receipt at the International Bureau: 22 July 2005 (22.07.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

1344236

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APPLICATION NUMBER: *60/536,444*
FILING DATE: *January 14, 2004*
RELATED PCT APPLICATION NUMBER: *PCT/US05/01295*

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Express Mail Label No. EU921343751US

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TITLE OF THE INVENTION (500 characters max)

RECONFIGURABLE FREQUENCY SELECTIVE SURFACES FOR REMOTE SENSING OF CHEMICAL AND BIOLOGICAL AGENTS

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15535 U.S. PTO
60/536444
011404

ENCLOSED APPLICATION PARTS (check all that apply)

☒ Specification *Number of Pages* 9
☒ Drawing(s) *Number of Sheets* 6
☐ CD(s), Number
☐ Other (specify)
☐ Application Data Sheet. See 37 CRF 1.76

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National Science Foundation, DMR 0213623

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Date January 14, 2004
REGISTRATION NO. (if appropriate)
Docket Number: 2003-2855

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

Practitioner's Docket No.: 2003-2855 **PATENT**

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of: D. Werner, et al.
Serial No.: Group No.:
Filed: January 14, 2004 Examiner:
For: RECONFIGURABLE FREQUENCY SELECTIVE SURFACES FOR REMOTE SENSING OF CHEMICAL AND BIOLOGICAL AGENTS

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RECONFIGURABLE FREQUENCY SELECTIVE SURFACES FOR REMOTE SENSING OF CHEMICAL AND BIOLOGICAL AGENTS

GOVERNMENT SPONSORSHIP

This work was supported by the National Science Foundation under Grant No. DMR 0213623. Accordingly, the US Government may have certain rights in this invention.

FIELD OF THE INVENTION

The present invention relates to reconfigurable frequency selective surfaces, and more particularly to a class of reconfigurable frequency selective surfaces that can be used for remote sensing of chemical and biological agents. The present invention also relates to reconfigurable switch elements that can be turned "ON" and "OFF" in response to remote stimuli, such as chemical and biological agents.

BACKGROUND OF THE INVENTION

Conventional Frequency Selective Surfaces ("FSS") consist of a metallic unit cell that is periodically replicated and printed on top of a thin dielectric substrate material. There has been a considerable amount of interest in FSS technology in recent years as they have been investigated for a variety of applications. These include electromagnetic filtering devices for reflector antenna systems, radomes, absorbers, and artificial electromagnetic bandgap materials. The majority of FSS designs have been considered for microwave and millimeter wave applications, however the concept is completely scalable to higher frequency ranges such as infrared and even optical frequencies.

In most FSS applications the geometry and material parameters are designed to produce a static frequency response. However, several groups have investigated the possibility of tuning or reconfiguring an FSS so that its frequency response can be shifted or altered altogether while in operation. This can be accomplished either by changing the electromagnetic properties of the FSS screen or substrate, by altering the geometry of the structure, or by introducing elements into the FSS screen that vary the current flow between metallic patches.

In the first class of Reconfigurable Frequency Selective Surfaces ("RFSS") the frequency response of the FSS is changed by altering the electromagnetic properties of the substrate. Several groups have realized this by utilizing a ferrite as the substrate material [3-8]. When a DC bias is applied across the ferrite substrate, the electrical properties are altered, making the electromagnetic waves appear electrically longer or shorter. By changing the DC bias the FSS can be tuned to higher or lower frequencies. However, there are some serious disadvantages associated with the concept of using ferromagnetic substrates. Ferrites have high mass, and large currents are required to maintain the DC bias across the substrate. Furthermore, setting up a DC bias over a large area of substrate is a complicated task. Nevertheless, a two-layer FSS with one or two ferrite substrates can be designed to switch between an absorber and a reflector at resonance by applying a DC bias to the substrate.

A related technique uses a liquid dielectric as the substrate. In this approach, a substrate cavity below the metallic screen is filled with a liquid dielectric or emptied to vary the permittivity. Varying the permittivity also varies the electrical wavelength inside the substrate, changing the frequency response. This technique has been demonstrated to tune the FSS frequency response, but it requires a complex design to properly handle the liquid substrate.

Another technique that alters the substrate properties uses a slotted FSS screen with a silicon substrate to produce a pass band at resonance under normal operation. However, when the silicon substrate is illuminated by an optical source with sufficient intensity, the silicon behaves like a conductor, making the pass band disappear. One final technique of interest involves using plasma to form a virtual FSS screen. Elements with a high plasma density behave like a metallic conductor. The plasma features can be altered thereby changing the frequency response of the virtual FSS.

The second category of RFSS design techniques are those in which the geometry of the metallic screen elements is altered in such a way as to effect a desired change in the frequency response. One technique that has been reported involves using two FSS screens with identical apertures or patch elements and a dielectric or spacing layer in between. The front and back screens are shifted vertically or horizontally with respect to each other, which produces a corresponding change in the frequency spectrum. The bandwidth and resonance positions both change when the screens are displaced.

A second reconfiguration technique has been introduced that is based on microelectromechanical systems ("MEMS") technology. The metallic elements of the FSS are designed to be able to lay flat on the substrate or tilt up to 90° from the substrate. Thus, the incident radiation sees a variable-size element depending on the tilt angle of the metallic patches. This method for tuning the response of an FSS has been successfully demonstrated by Gianvittorio et al. (*IEE Electronics Letters*, Vol. 38, No. 25, Dec. 2002). However, it requires complex fabrication techniques and the ability to produce an external electromagnetic field in order to mechanically control the element positions.

The final class of RFSS to be considered incorporates circuit elements into the metallic screen that can be used to vary the current between patch elements. A technique has been proposed for controlling the response of an FSS by interconnecting metallic patches in its screen with lumped variable reactive elements (C. Mias, *IEE Electronics Letters*, Vol. 39, No. 9, May 2003). Although variable reactive elements were not used in experiment, the effect of varying reactive loads between patches was shown through numerical simulations to shift the position of stop bands. This technique was taken a step further by including varactor diodes to tune the stop band of an FSS absorber.

Another option that has been investigated is to use PIN diodes as switches between metallic patch elements. PIN diodes either allow or inhibit current flow between patch elements depending on the voltage bias applied across the diode. Thus, they can be used to make a resonance disappear, or they can drastically change a resonance location based on the RFSS design. The active FSS described by Chang, et al. also incorporates a ferrite substrate so that the resonant frequency may be tuned by biasing the ferrite substrate or by switching the PIN diodes to go from a transmitting to a reflecting mode and back again (*IEEE Proc. Microwaves, Antennas and Propagation*, Vol. 143, No. 1, Feb. 1996). One difficulty with using PIN diodes as switches in RFSS is the added complexity of incorporating bias lines into the design.

Several interesting applications have been suggested for RFSS that switch on or off using diodes. The design procedure for a horn antenna that has two tapered walls was described by Philips, et al. (*IEE Electronics Letters*, Vol. 31, No. 1, Jan. 1995). The outer wall of the antenna is made of a solid metallic sheet while the second, narrower wall consists of a RFSS that incorporates diodes so that it can be switched from transmitting to reflecting.

In the transmitting state, the horn antenna has a relatively wide aperture, but when the RFSS is switched to a reflecting state it acts as the inner wall of the horn antenna giving it a narrower aperture. The same type of active RFSS was proposed for building walls in order to control the transparency of the structure at a given radio frequency.

SUMMARY OF THE INVENTION

The present invention describes a new passive Reconfigurable Frequency Selective Surface comprising a periodic array of arbitrarily shaped, metallic patches interconnected by a matrix of switches. The invention advantageously enables each switch or switch type to be independently addressed by applying remote stimuli such as light or analyte (chemical and/or biological). The unit cell formed by the grid of patches and switches can be optimized (e.g., via a Genetic Algorithm) for a desired frequency response by simply adjusting the ON/OFF state of each switch in the grid. Once the optimal switch settings have been determined, they can be conveniently stored in a look-up table for later use. This method is superior to previous RFSS design concepts because it truly exploits the flexibility afforded by incorporating switches into FSS screens. It is demonstrated by this invention, through the examples provided herein, that a very simple set of patch elements interconnected with switches can be tailored to meet a wide variety of frequency response requirements.

DETAILED DESCRIPTION OF THE INVENTION

The present invention describes a new passive Reconfigurable Frequency Selective Surface comprising a periodic array of arbitrarily shaped metallic elements interconnected by a matrix of switches, where each switch or switch type can be independently addressed by applying external stimuli (light, chemical or biological analyte, etc.). This allows the geometry of the passive FSS screen to be altered by reconfiguring the matrix of switches (i.e., "ON" and "OFF") such that different switch settings result in a unique reflection or transmission response. The RFSS can be designed to produce changes in the frequency and/or polarization response of the reflected or transmitted spectra of the surface in response to the external stimuli. Thus, the reconfiguration results in a change in the electromagnetic properties or signature of the FSS, which can be interrogated and detected remotely using sources and detectors that are sensitive in the frequency range of interest. Such RFSSs have

application in diverse fields such as reconfigurable electromagnetic shielding and remote chemical and biological sensing.

Conventional Frequency Selective Surfaces consist of a metallic unit cell that is periodically replicated and printed on top of a thin dielectric substrate material. The geometry of the unit cell can be designed to transmit or reflect certain frequency bands. The present invention achieves a reconfigurable FSS by specifying a fixed metallic pattern and then introducing switches connecting the fixed metallic segments which may be turned "ON" or "OFF" to achieve a desired frequency response. **Figure 1** is an example of a reconfigurable FSS geometry where switch elements connect a subset of fixed metallic dipoles elements. The resulting transmission and reflection spectra for the cases when all of the switches are either "ON" and "OFF" is given in **Figure 2 a-b**.

It is evident from these spectra that the frequency at which the single transmission and reflection passband is observed can be changed by turning on the switches, and hence changing the effective dimensions of the overall dipole element (i.e., fixed metal plus switch). The absolute passband frequencies and the difference in "ON" and "OFF" passband frequency can be easily tailored by adjusting the relative dimensions of the fixed metal dipole and connecting switch elements. For instance, the FSS can be configured for a frequency response to a linearly polarized incident plane wave. In addition, the FSS designs of the present invention can be scaled to produce surfaces with a response at frequencies in the microwave, infrared, and visible due to the inherent scalability of the electromagnetic theory used in their design.

In another embodiment of the invention, the FSS incorporates a multitude of different switches that can be turned ON and OFF either individually or in groups. **Figures 3 – 5** depict a FSS pattern that is optimized using a genetic algorithm approach to provide 2 stop bands at 3.5 and 6 THz when the switches shown in blue in Figure 4 are turned "ON". Several different types of approaches can be used to optimize the present RFSS designs, including but not limited to those based on evolutionary programming, genetic algorithms and particle swarm optimization. **Figures 6 – 7** show an example in which the FSS has been optimized to provide 3 stop bands at 4, 7 and 9 THz when the switches shown in blue in Figure 6 are turned "ON".

These designs may be fabricated using the same surface if each of the switches' locations can be addressed individually. However, many applications rely on external stimuli to provide the excitation required to turn the switches "ON" or "OFF". This includes chemical and biological sensing applications, where the switch elements are fabricated from materials that change their conductivity state in the presence of a particular chemical or biological analyte. In such case, groups of switches typically respond in unison to a particular chemical or biological analyte. Accordingly, where there are shared switches in the FSSs, they should be implemented using two different starting surfaces.

In a further embodiment of the invention, multiple types of switch elements are incorporated into a single FSS. In this embodiment, each of the different types of switch elements may be designed to respond differently to different chemical analyte mixtures to produce an FSS with unique passband characteristics that depend on the switch element settings. An example of such a surface along with its response is shown in **Figures 8** and **9**. For example, there are two sets of switches, blue and green, which can be independently turned "OFF," or "ON." When both the blue and green switches are "OFF," the FSS comprised of dipoles produces a single stop band at 22.3 THz, when the blue switches are "ON," the size of the dipoles doubles so that the FSS produces a single stop band at 11.3 THz, when the green switches are "ON," the short and long dipoles alternate so that the FSS produces dual stop bands at 9.5 and 18.3 THz, and when both the blue and green switches are "ON," the longer dipoles alternate with infinite metal strips so that the FSS acts as a high pass filter with a stop band at 11.3 THz. In this way, each state (i.e., switch setting) of the FSS produces a unique microwave, infrared, or optical signature. As described previously, a genetic algorithm or other optimization approach can be used to determine the optimal pattern of switch settings required in order to achieve a set of desired frequency responses (i.e., signatures).

The genetic algorithm is capable of optimizing the reconfigurable dipole pattern for a variety of target frequency responses. These optimized configurations can be placed in a database to be retrieved when reconfiguring the FSS to a desired frequency response. Although it may require some time to optimize the pattern for a set of target frequency responses, the optimizations only need to be performed once. Specific configurations can

then be quickly retrieved from a database and implemented to reconfigure the FSS in real time or analyze the resulting FSS signature.

Another embodiment of the invention, shown in **Figure 10**, comprises a cell geometry that can be used to produce a reconfigurable frequency response for both TE and TM polarizations. By using a genetic algorithm technique on this structure, the frequency responses for TE and TM polarizations can be individually optimized. This cell geometry contains both a fixed cross-dipole pattern and a set of switches, which can be individually turned on (connected) or off (disconnected). The goal is to specify one target frequency response for the TE polarization and another target frequency response for the TM polarization and allow the GA to find a set of switch values that achieves the target response. This embodiment of the invention, illustrated in **Figure 11**, indicates the switch configurations that are required to produce the responses shown in **Figure 12**. This particular design contains a reconfigurable cell geometry that is capable of producing either the same or a completely different frequency response for vertical and horizontal polarizations.

The cell geometry shown in **Figure 10** comprises a periodic metallic crossed-dipole pattern interconnected by a set of switches, which may be individually activated (turned on) or deactivated (turned off). The goal in this case is to identify the optimal switch settings that would lead to a desired target frequency response for horizontal polarization and another target frequency response for vertical polarization. **Figure 11** shows a reconfigurable FSS pattern that has been optimized (in this case using a genetic algorithm technique) to produce two stop-bands, one at 8 THz for a TE (Transverse Electric) polarized wave and the other at 4 THz for a TM (Transverse Magnetic) polarized wave. The genetic algorithm is used to determine which switches should be turned on and which ones should be turned off in order to produce the desired TE and TM responses. The transmission and reflection spectrums corresponding to this design are shown in **Figure 12**. These examples demonstrate the flexibility of the reconfigurable FSS design methodology, wherein the crossed-dipole pattern can be optimized for a variety of target frequency responses and the corresponding switch settings can be stored in a look-up table for future reference.

There are many uses for this technology, including but not limited to, its application to the development of new remote sensing systems for chemical and/or biological agents. In

these systems, the type of switches used in the RFSS are specifically designed to turn "ON" or "OFF" upon exposure to a variety of chemical and/or biological agents. Deployed sensors of this type can be interrogated remotely via directed radio frequency, infrared, and visible electromagnetic energy, allowing the frequency response of the reflected or transmitted signals to be correlated with a known set of environmental responses.

The FSS switches can be fabricated using materials that change conductivity state in the presence of certain chemical or biological analytes. Examples of such materials include chemically or biologically sensitive conductive polymers. The most common conductive polymers include derivatives of polythiophenes, polypyrole and polyanaline, which have been shown to change their conductivity state by many orders of magnitude in the presence of chemical analytes. These conductive polymers have been shown to have sufficiently high conductivity in the frequency range of interest for these sensor applications (microwave and infrared) to serve as effective switch elements for the FSS. The conductivity of such materials has been enhanced by building percolation threshold composites that include carbon black, nanowires and carbon nanotubes. These conductive polymer materials are often extremely sensitive but not selective to particular analytes (i.e., conductivity changes are observed for more than one chemical). Moreover, the change in conductivity is proportional to the concentration of chemical that is present. Other molecular systems are also being developed with excellent selectivity to particular chemical and biological species. The materials used to fabricate the switches of the instant invention are not limited to conductive polymers and their derivatives, but instead include any class of materials that is capable of changing its conductivity state in the presence of chemical or biological analytes.

Incorporating chemically or biologically sensitive switches in predefined patterns on the RFSS allows it to automatically reconfigure to produce a unique optical signature in the presence of different chemical analyte mixtures. The entire sensor system is completed by remotely illuminating the FSS with a source of radiation of the desired frequency range and identifying the presence of certain chemicals based on the reflection or transmission spectra that are generated. For instance, a military application of the sensor system involves applying the RFSS on an unmanned aerial vehicle or as part of an unattended ground sensor, which can be remotely interrogated to detect the presence of chemical agents. This has advantages over other sensing approaches because the entire sensor is passive and does not

require an on-board source of energy. Moreover, such surfaces can be fabricated on flexible substrate materials such that they can be easily mounted onto a variety of platforms. Militarily significant examples include tanks and next generation soldier suits.

While the above-mentioned embodiments modeled the switches as ideal (i.e., either "ON" or "OFF"), the present invention also incorporates a more realistic response where the chemically or biologically sensitive switches are not completely selective to different chemicals and have a range of conductivity states between "ON" and "OFF". In such case, the signature of the RFSS is more complicated to interpret. However, this problem is similar to those being addressed by other sensor platforms, including on-chip conductivity based sensors. In these sensors, the sensor chip is often trained under a variety of exposure conditions prior to use. The response that is collected during operation is then evaluated using pattern recognition algorithms (e.g., neural networks etc.) to determine the chemical analyte mixture present. This approach can also be extended to RFSS patterns beyond those described herein. Genetic algorithms can be used to design fractal surfaces that produce a desired frequency response that is frequency and/or polarization sensitive. Such patterns are particularly useful in many practical samples when it is necessary to accommodate properties such as lossy switches, metals, and substrates and surfaces with finite substrate thickness.

While the invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various alterations in form and detail may be made therein without departing from the spirit and scope of the invention.

FIGURES

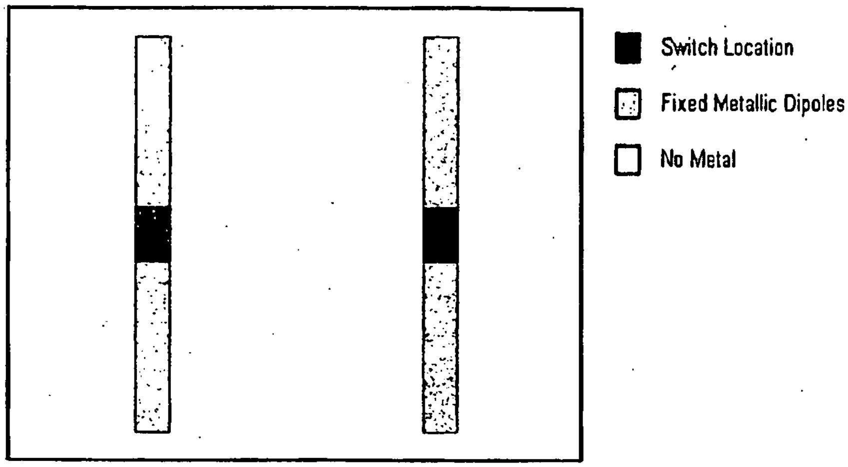


Figure 1. Reconfigurable FSS Geometry with 2 Configurations.

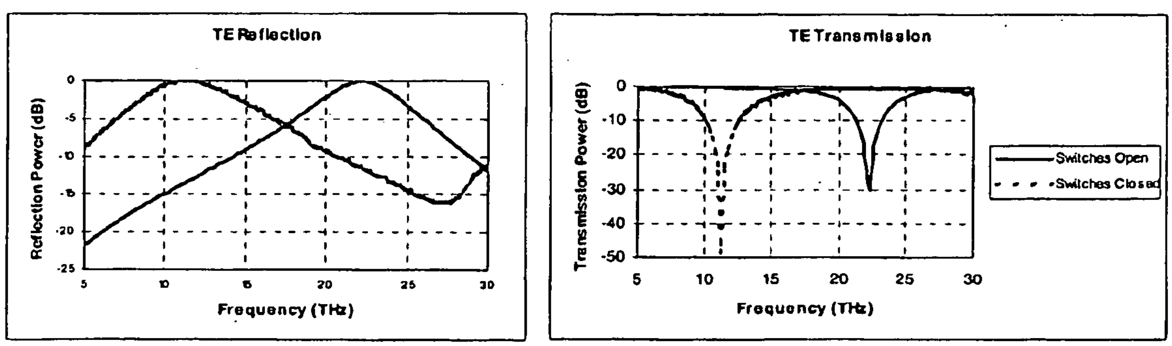


Figure 2. Transmission and Reflection Spectrums for Geometry in Figure 1.

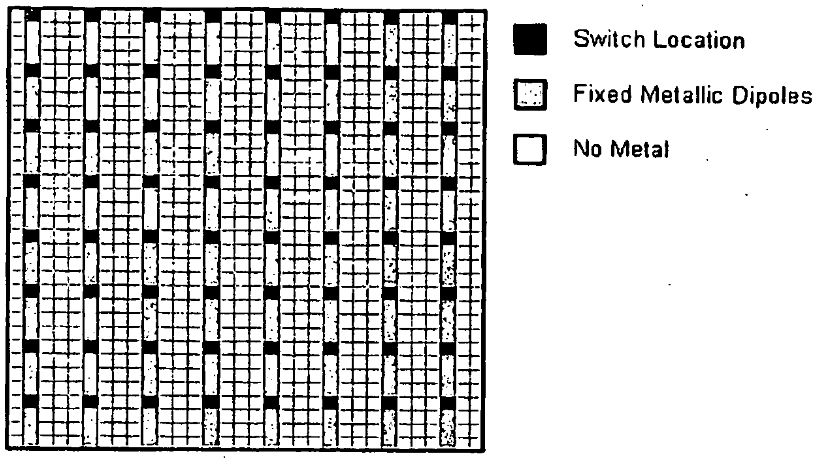


Figure 3. Reconfigurable FSS Geometry for Linear Polarization. Possible Switch Locations are Shown in Blue. Each Pixel is 1x1 Microns and the Unit Cell is 32x32 Microns.

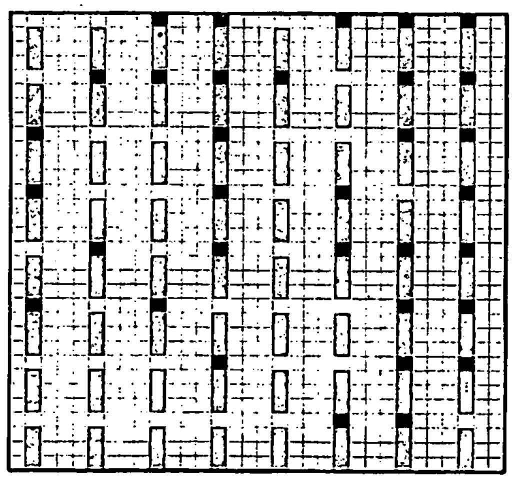


Figure 4. Geometry Optimized for 2 Stop Bands. Each Pixel is 1x1 Microns and the Unit Cell is 32x32 Microns.

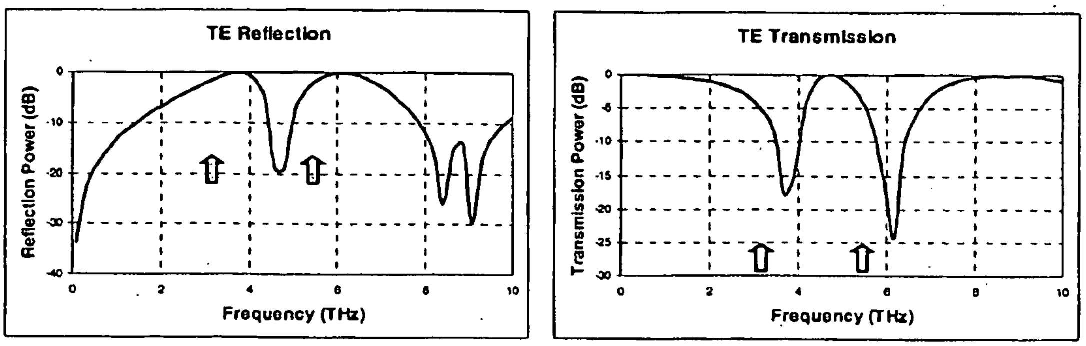


Figure 5. Transmission and Reflection Spectrums for Geometry in Figure 4.

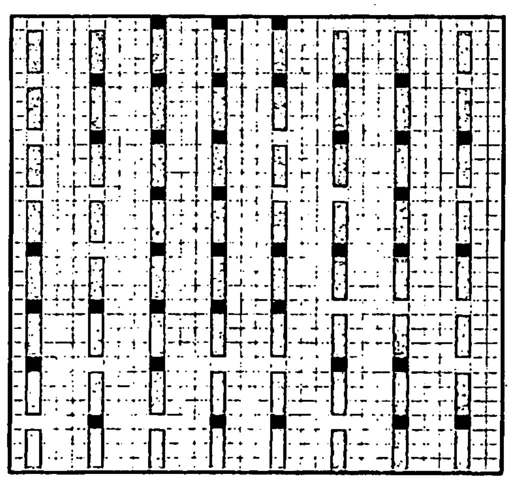


Figure 6. Geometry Optimized for 3 Stop Bands. Each Pixel is 1x1 Microns and the Unit Cell is 32x32 Microns.

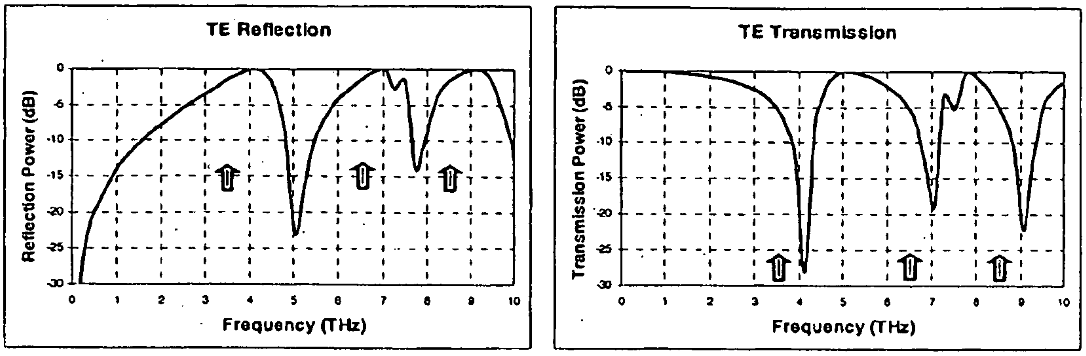


Figure 7. Transmission and Reflection Spectrums for Geometry in Figure 6.

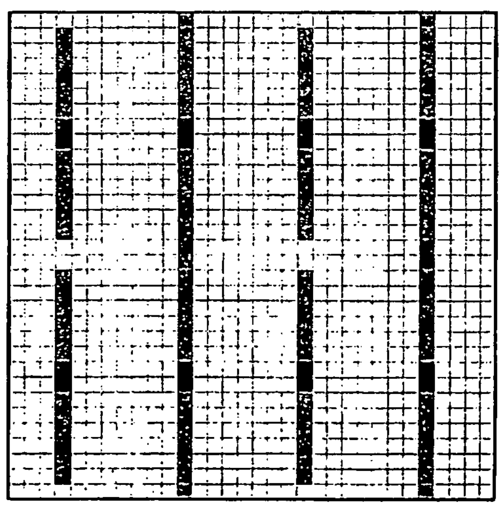
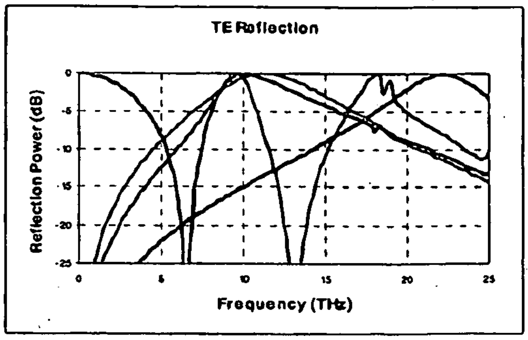


Figure 8. Reconfigurable FSS Geometry Demonstrating Two Independently Activated Sets of Switches. Each Pixel is 1x1 Microns and the Unit Cell is 32x32 Microns.



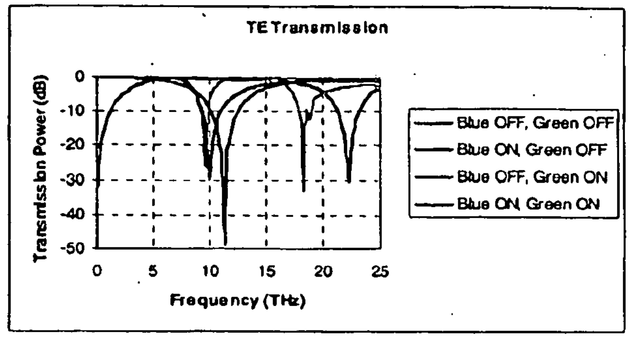


Figure 9. Transmission and Reflection Spectrums for all Four Possible Switch Settings Corresponding to the Geometry Shown in Figure 8.

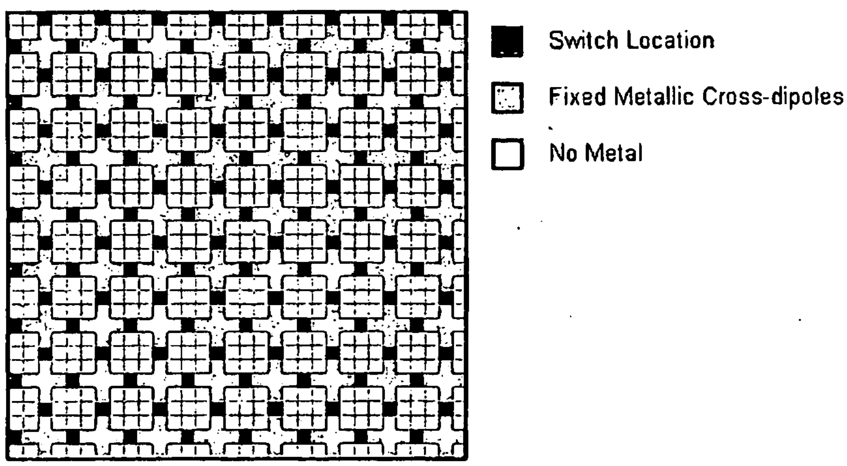


Figure 10. Reconfigurable FSS Geometry for Both TE and TM Polarizations. Possible Switch Locations are Shown in Blue. Each Pixel is 1x1 Microns and the Unit Cell is 32x32 Microns.

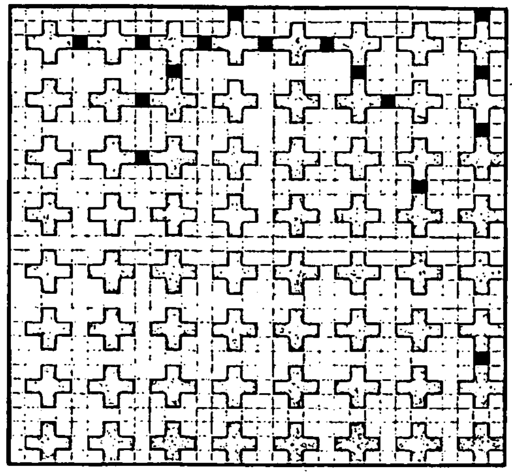


Figure 11. RFSS Geometry Optimized to Produce Two Stop-bands, One at 8 THz and One at 4 THz for a TE and a TM Polarized Wave Respectively.

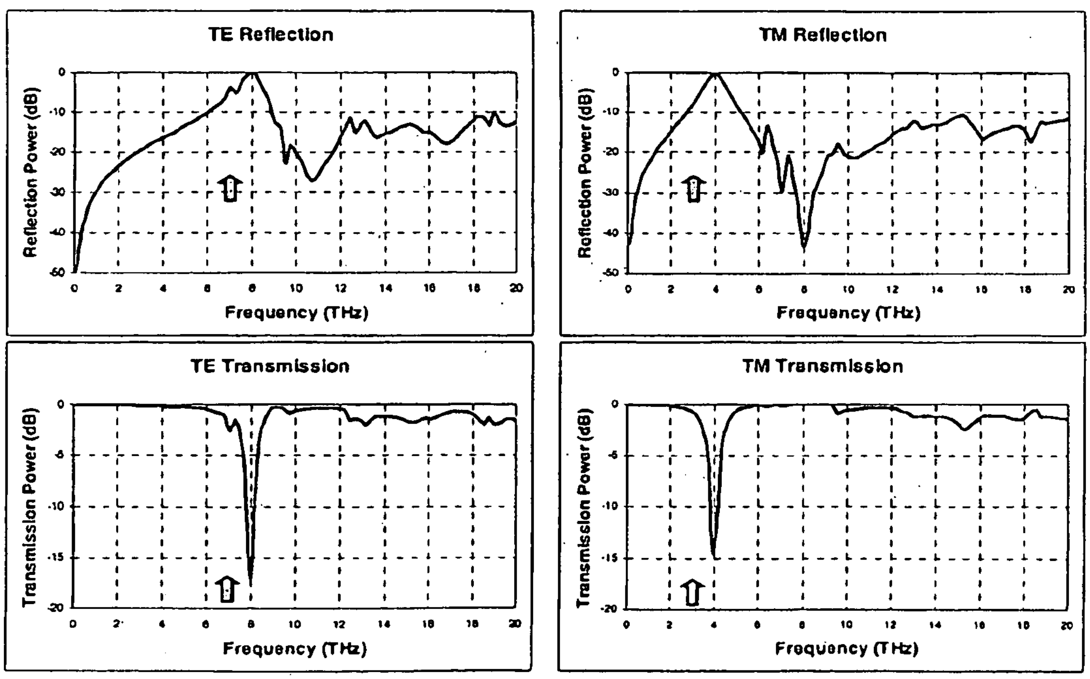


Figure 12. Transmission and Reflection Spectrums for RFSS Geometry Shown in Figure 11.

PATENT COOPERATION TREATY

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Applicant's or agent's file reference PST-16952/36	**IMPORTANT NOTIFICATION**
International application No. PCT/US2005/001295	International filing date *(day/month/year)* 14 January 2005 (14.01.2005)
International publication date *(day/month/year)*	Priority date *(day/month/year)* 14 January 2004 (14.01.2004)
Applicant THE PENN STATE RESEARCH FOUNDATION et al	

1. By means of this Form, which replaces any previously issued notification concerning submission or transmittal of priority documents, the applicant is hereby notified of the date of receipt by the International Bureau of the priority document(s) relating to all earlier application(s) whose priority is claimed. Unless otherwise indicated by the letters "NR", in the right-hand column or by an asterisk appearing next to a date of receipt, the priority document concerned was submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b).

2. *(If applicable)* The **letters "NR"** appearing in the right-hand column denote a **priority document which, on the date of mailing of this Form, had not yet been received by the International Bureau** under Rule 17.1(a) or (b). Where, under Rule 17.1(a), the priority document must be submitted by the applicant to the receiving Office or the International Bureau, but the applicant fails to submit the priority document within the applicable time limit under that Rule, **the attention of the applicant is directed** to Rule 17.1(c) which provides that no designated Office may disregard the priority claim concerned before giving the applicant an opportunity, upon entry into the national phase, to furnish the priority document within a time limit which is reasonable under the circumstances.

3. *(If applicable)* **An asterisk (*)** appearing next to a date of receipt, in the right-hand column, denotes a **priority document submitted or transmitted to the International Bureau but not in compliance with Rule 17.1(a) or (b)** (the priority document was received after the time limit prescribed in Rule 17.1(a) or the request to prepare and transmit the priority document was submitted to the receiving Office after the applicable time limit under Rule 17.1(b)). Even though the priority document was not furnished in compliance with Rule 17.1(a) or (b), the International Bureau will nevertheless transmit a copy of the document to the designated Offices, for their consideration. In case such a copy is not accepted by the designated Office as the priority document, Rule 17.1(c) provides that no designated Office may disregard the priority claim concerned before giving the applicant an opportunity, upon entry into the national phase, to furnish the priority document within a time limit which is reasonable under the circumstances.

Priority date	Priority application No.	Country or regional Office or PCT receiving Office	Date of receipt of priority document
14 January 2004 (14.01.2004)	60/536,444	US	22 July 2005 (22.07.2005)

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